The Art of Image Processing
— Operators and Applications

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Outline

1. Introduction to Image Processing.
2. Image Perception.
3. Image Enhancement and Restoration.
4. Image Interpolation and Visualization
5. Image Analysis.
6. Computed Tomography.
7. Image and Video Compression.

1. Introduction

- Digital Image: a two dimensional array of pixels.
  - Size (or resolution) of an image:
    width: N pixels, height: M pixels.
  - Precision of pixels:
    2^n amplitude levels $\Rightarrow$ n bits per pixel.
  - Overall data file size: $N \times M \times n$ bits
- Digital Video: a sequence of digital image frames.
  - Frame rate of a video sequence:
    f frames per second.
  - Overall data rate: $N \times M \times n \times f$ bits per second.

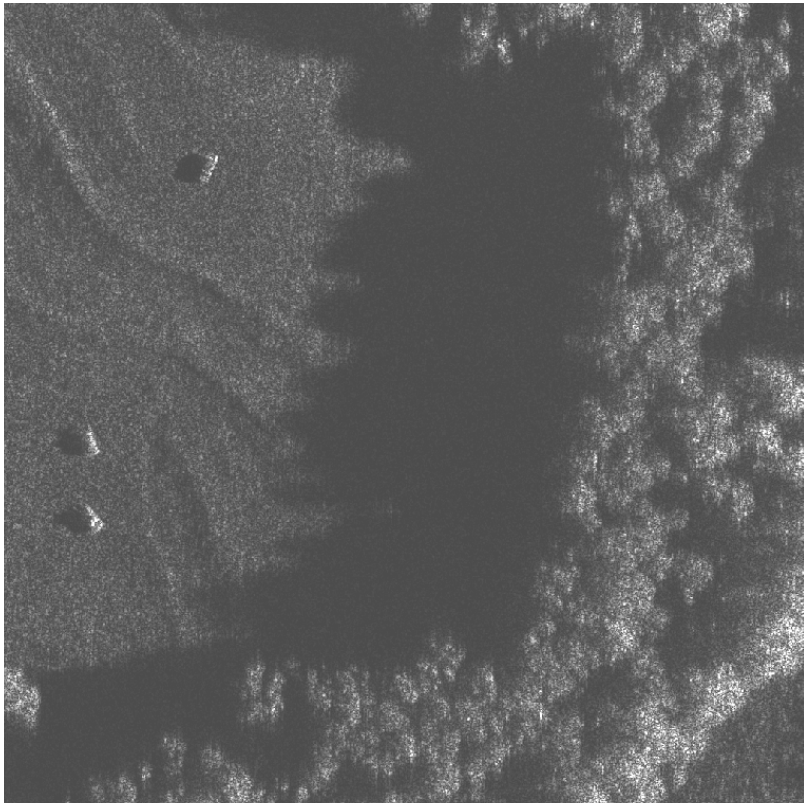
Image Example

LENA, 512x512, true color (24 b/p), 786432 bytes.

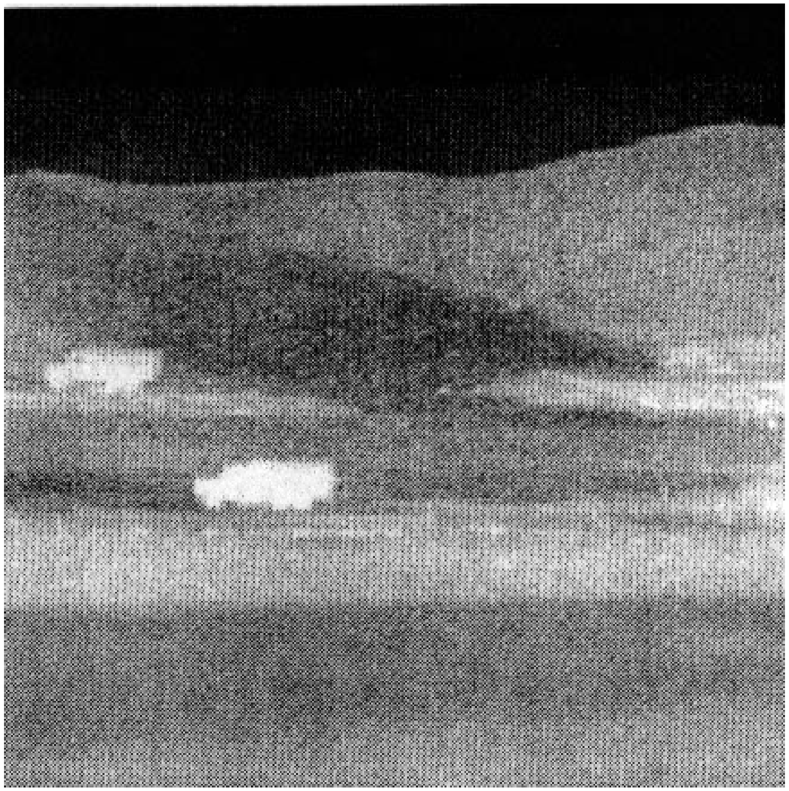
Image Examples

Size: 2048x2560

Image Examples

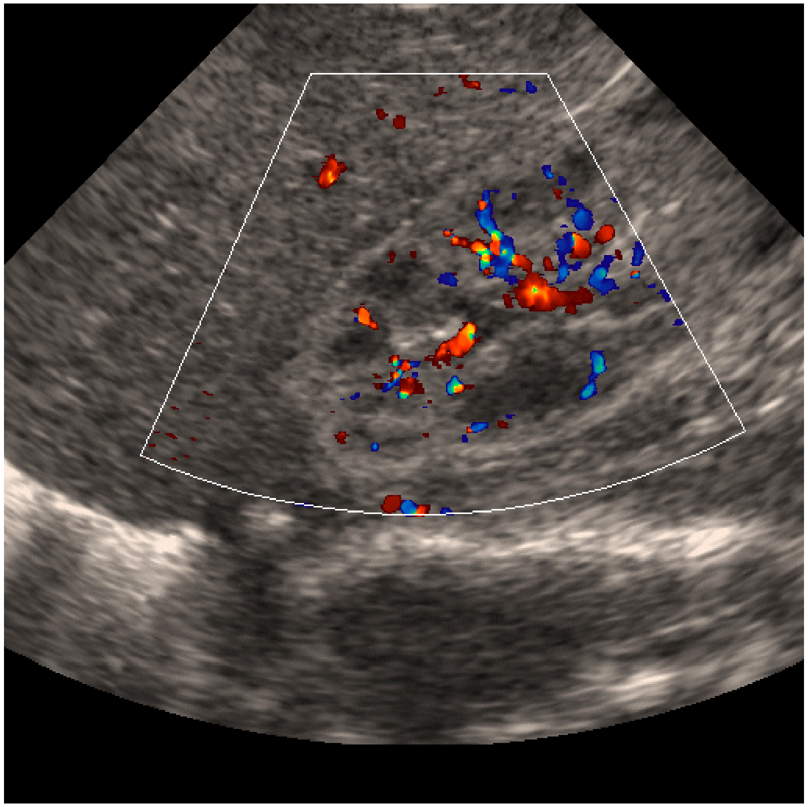


Synthetic Aperture Radar



Infrared

Image Examples



Ultrasound

X-ray

Graphic Example

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Video Example

AKIYO, 352x288 (CIF), 24 b/p, 30 f/s, 72.99 Mbits/s.

Animation Example

Image Processing

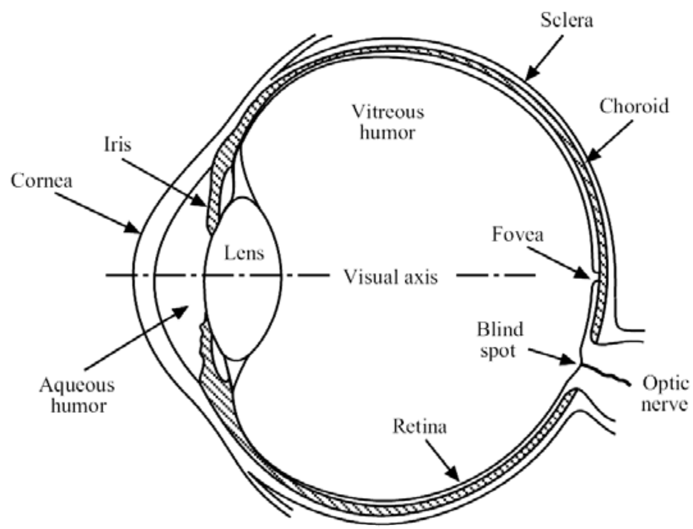
- Image Processing is to perform numerical operations on higher dimensional signals such as images and video sequences.
- The objectives of image processing include:
  - Improving the appearance of the visual data

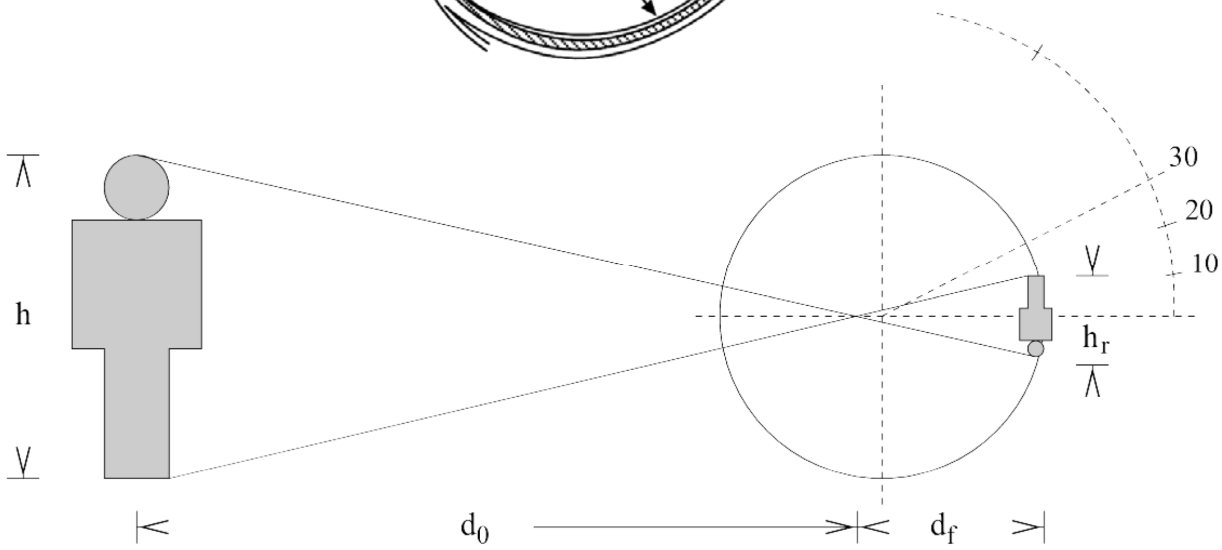
    image enhancement, image restoration
  - Extracting useful information

    image analysis, reconstruction from projection
  - Representing the image in an alternate and possibly more efficient form

    transformation, image compression

2. Image Perception





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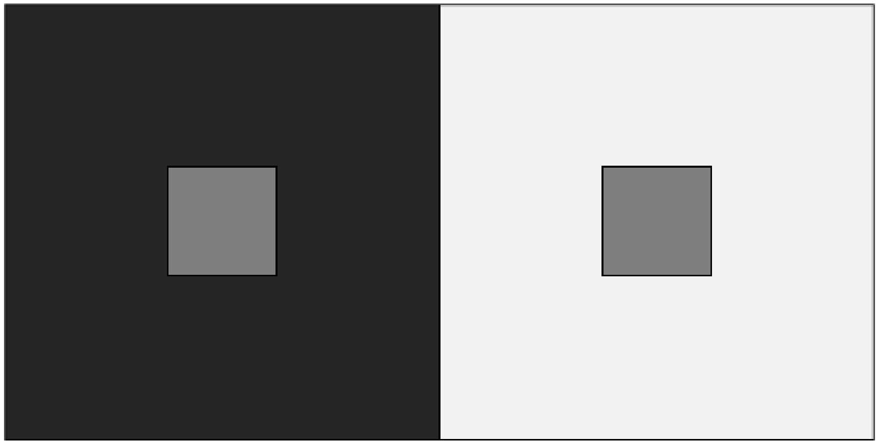
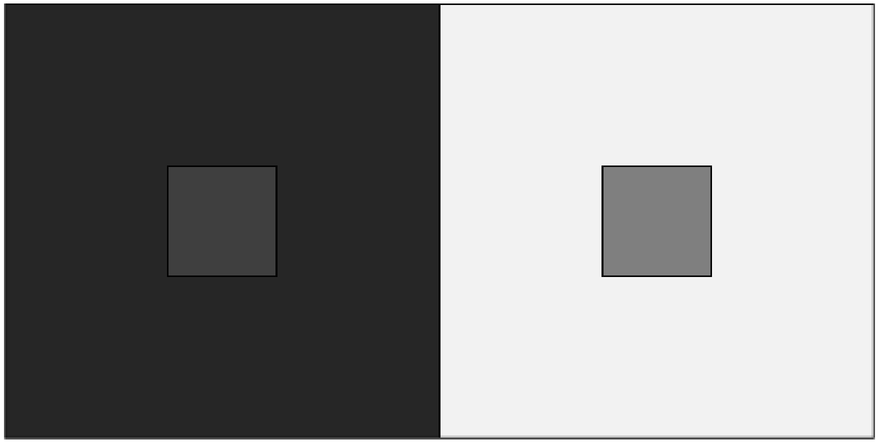
Brightness and Contrast

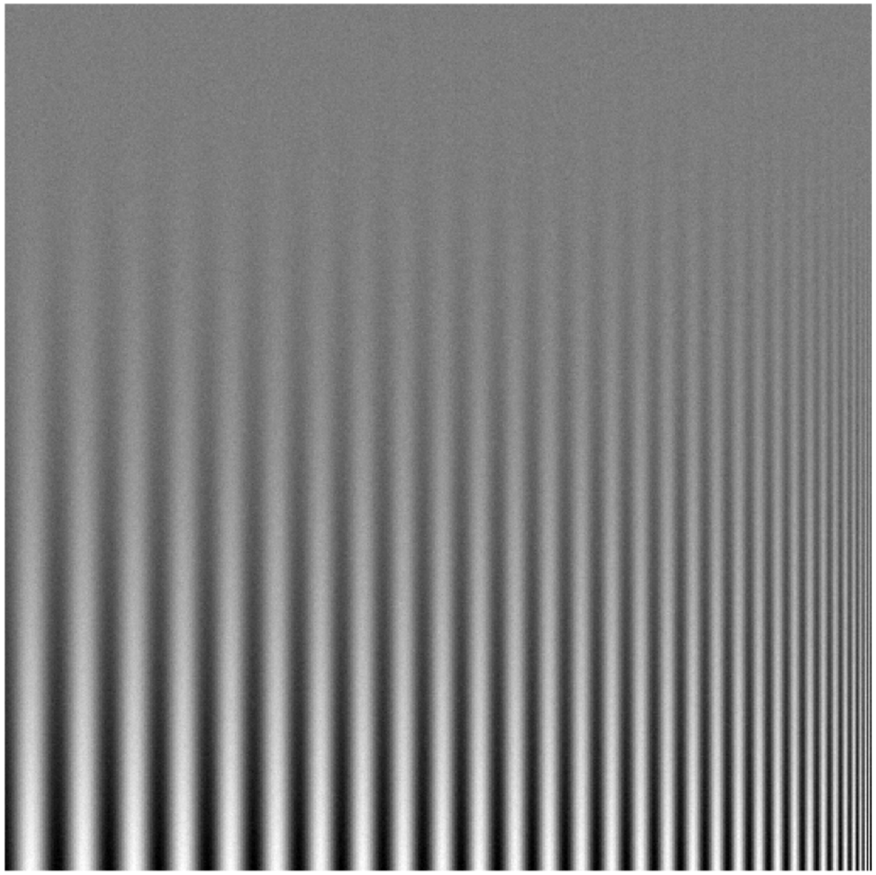


(a)

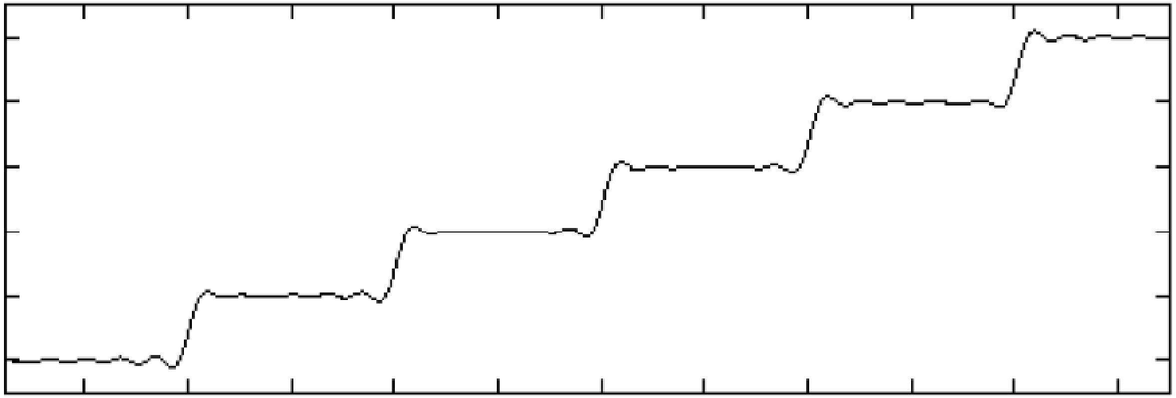


(b)

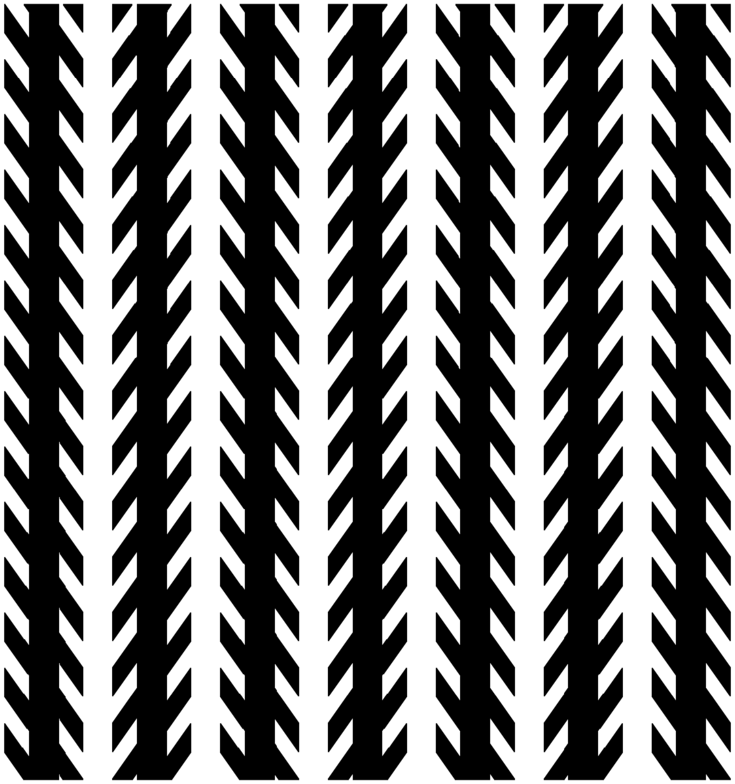
Spatial Frequency Response



Physical Model of Brightness Transition



Non-Linear Characteristics

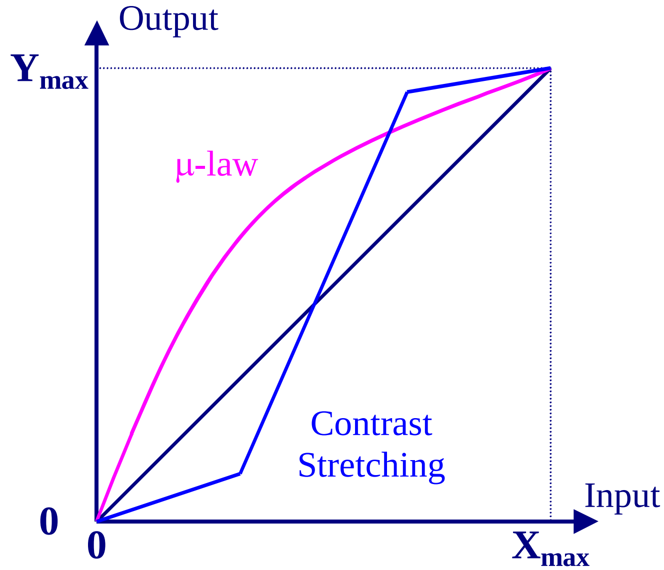


3. Image Enhancement and Restoration

- Image enhancement and restoration refers to a general class of operators that can improve the quality of images for various applications.
- In general, the input of these operators are somehow distorted or damaged images.
- ***Image enhancement*** techniques do not assume any knowledge on the distortion process of the input images. Therefore they are usually simple and ad-hoc.
- ***Image restoration*** techniques are able to use the knowledge of the image distortion process to restore the original image through a mathematical inverse process. So they are usually more effective but far more complex.

Pixel Amplitude Modification

- Pixel amplitude modification is a general approach where the amplitude of each pixel is changed individually according to a pre-defined rule.
- This approach is usually simple, and yet effective in improving the brightness and contrast of an image.

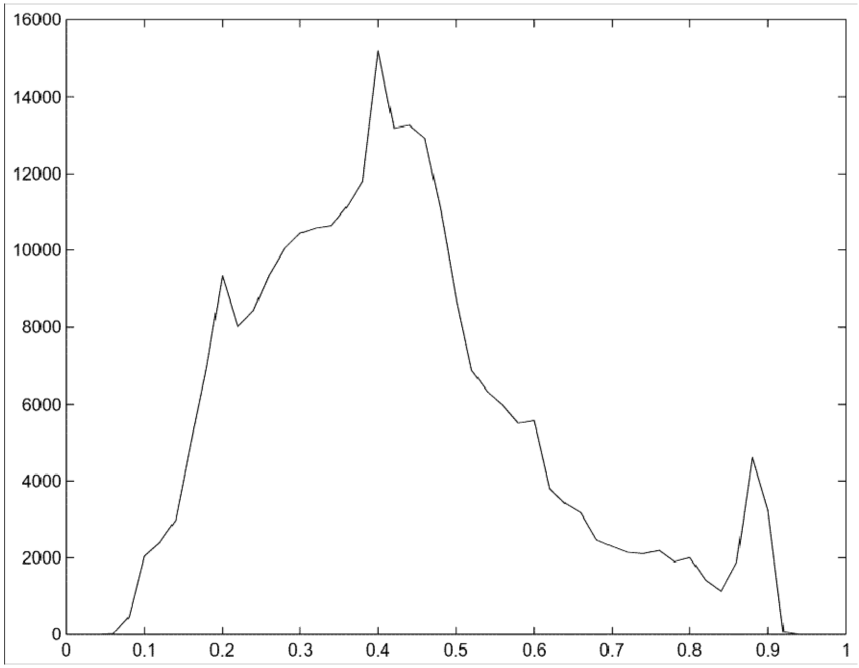


Histogram Modification

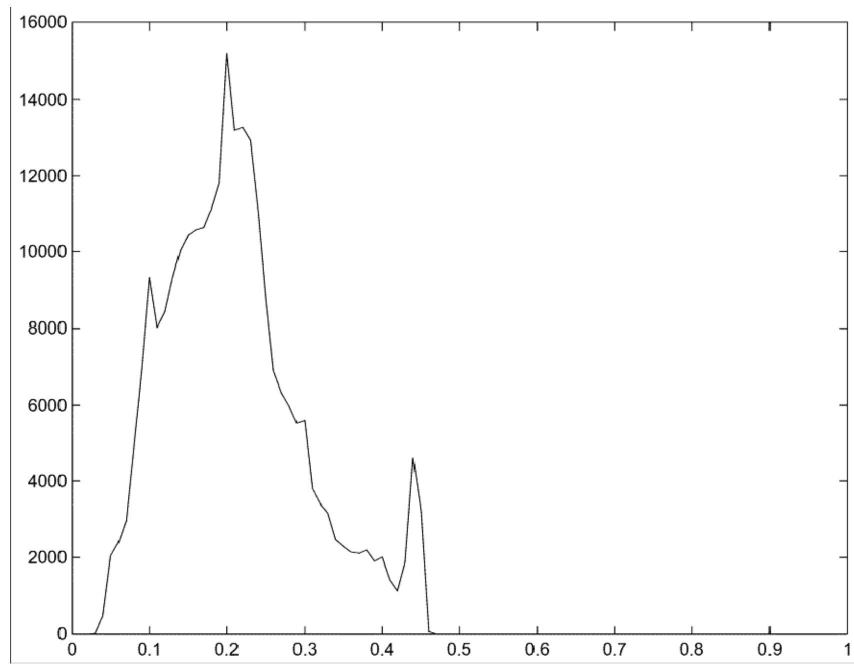
- The histogram of an image is a mapping function between the input amplitude value and the number of occurrences of that value in the image. It can be viewed as a probability density function (pdf) of all the pixels.
- The histogram is a effective indicator of the contrast condition of an image:
  - An evenly distributed histogram -- a good contrast.
  - A peak-shaped histogram -- a poor contrast.
- Histogram modification or equalization is to re-map each pixel to a new amplitude such that the resulting histogram will have an relatively uniform distribution.

Histogram Example

Original

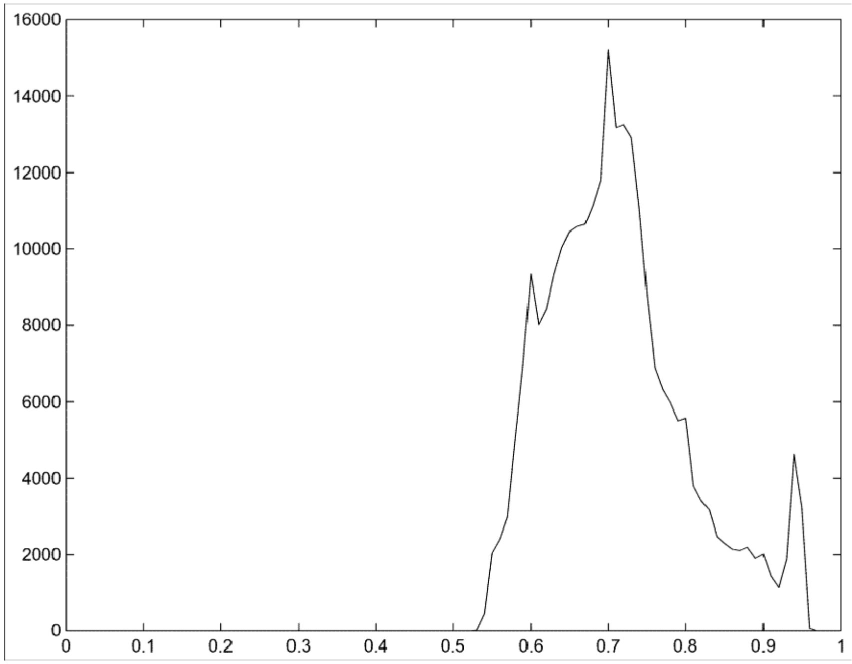


Histogram Example (*cont.*)



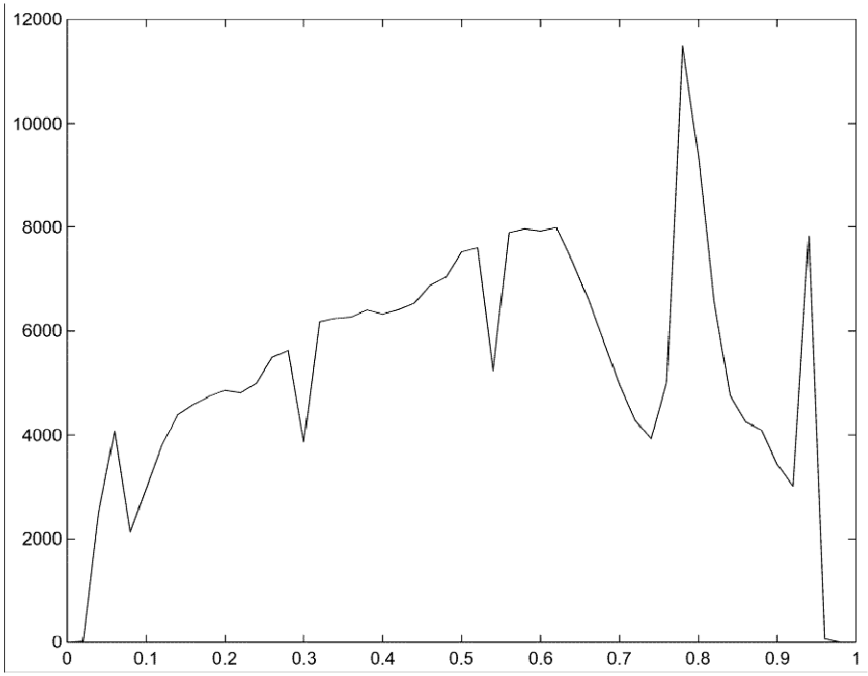
Poor contrast

Histogram Example (*cont.*)



Poor contrast

Histogram Example (*cont.*)



Enhanced contrast

Direct Filtering

- Filtering, as an essential digital signal processing (DSP) operation, provides an obvious solution to many image enhancement problems.
- For image filtering, finite impulse response (FIR) filters and non-linear morphological filters are popular choices because of their simplicity.
- Direct filtering can be used to achieve:
  - Edge enhancement – high-pass filters,
  - Noise reduction – low-pass filters.
- The performance can usually be improved through adaptive filtering based on local and directional variations.

Smoothing and Sharpening Examples

Smoothing

Sharpening

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Noise Reduction Example

Salt pepper noise

De-noise

Inverse Filtering

- If the distortion process of a damaged image is known, sometime we can model such a process as a filtering operation,

$$\mathbf{X_d(\Omega_1, \Omega_2) = X(\Omega_1, \Omega_2)H(\Omega_1, \Omega_2).}$$

- Image restoration can therefore be achieved through an inverse filtering operation,

$$\mathbf{X(\Omega_1, \Omega_2) = X_d(\Omega_1, \Omega_2)G(\Omega_1, \Omega_2),} \text{ where}$$

$$\mathbf{G(\Omega_1, \Omega_2) = 1/H(\Omega_1, \Omega_2)}.$$

- Issues regarding the stability of this inverse filter $\mathbf{G(\Omega_1, \Omega_2)}$ has to be carefully addressed.

Image Distortion Example

Motion blur is caused by a moving object or moving camera with a slow shutter which results multiple shifted images overlapping together.

$$H(\Omega_1,\Omega_2) = \frac{2\mathrm{Sin}(V\Omega_1 T/2)}{V\Omega_1},$$

$$G(\Omega_1,\Omega_2) = \frac{V\Omega_1}{2\mathrm{Sin}(V\Omega_1 T/2)}.$$

Wiener Filter

- Frequently the image distortion process also contains an additive noise component, which can not be easily removed through the inverse filtering,

$$X_d(\omega_1, \omega_2) = X(\omega_1, \omega_2)\, H(\omega_1, \omega_2) + N(\omega_1, \omega_2).$$

- The ***Wiener filter*** is the least mean square error restoration in this situation. It requires the information of the distortion filter and the statistics of the original image and the noise,

$$G(\omega_1,\omega_2) = \frac{\Gamma_{xx}(\omega_1,\omega_2)H^*(\omega_1,\omega_2)}{|H(\omega_1,\omega_2)|^2\,\Gamma_{xx}(\omega_1,\omega_2)+\Gamma_{NN}(\omega_1,\omega_2)}.$$

4. Image Interpolation and Visualization

- Visualization usually involves the integration of several images taken from different
  - Direction
  - Position
  - Time
  - Modality
- Visualization generally requires geometric interpolation of pixel values in 3-D space.

Visualization Example

Snow Mountain

5. Image Analysis

- Image analysis is to identify and extract useful information from an image or a video scene, typically with the ultimate goal of forming a decision.
- Image analysis is the center piece of many applications such as remote sensing, robotic vision and medical imaging.
- Image analysis generally involves basic operations:
  - Pre-processing,
  - Object representation,
  - Feature detection,
  - Classification and interpretation.

Image Segmentation

- Image segmentation is an important pre-processing tool. It produces a binary representation of the object with features of interest such as shapes and edges.
- Common operations include:
  - Thresholding: to segment an object from its background through a simple pixel amplitude based decision. Complicated thresholding methods may be used when the background is not homogeneous.
  - Edge detection: to identify edges of an object through a set of high-pass filtering. Directional filters and adaptive filters are frequently used to achieve reliable results.

Segmentation Examples

Thresholding

Edge detection

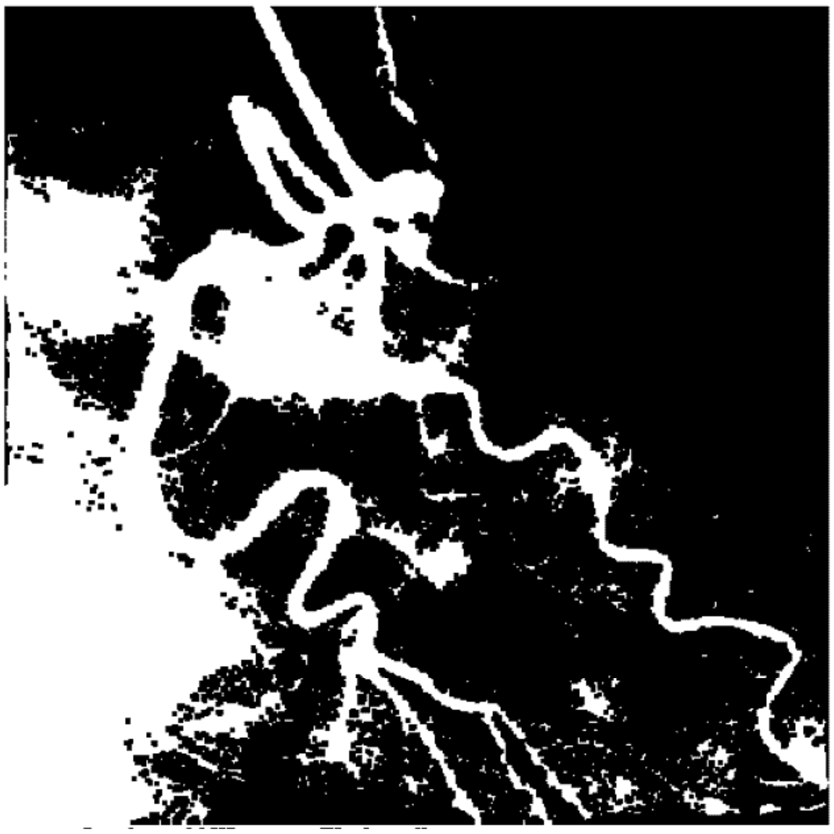
Morphological Operation Examples (1)

Original

Opening

Morphological Operation Examples (2)

Original



Closing

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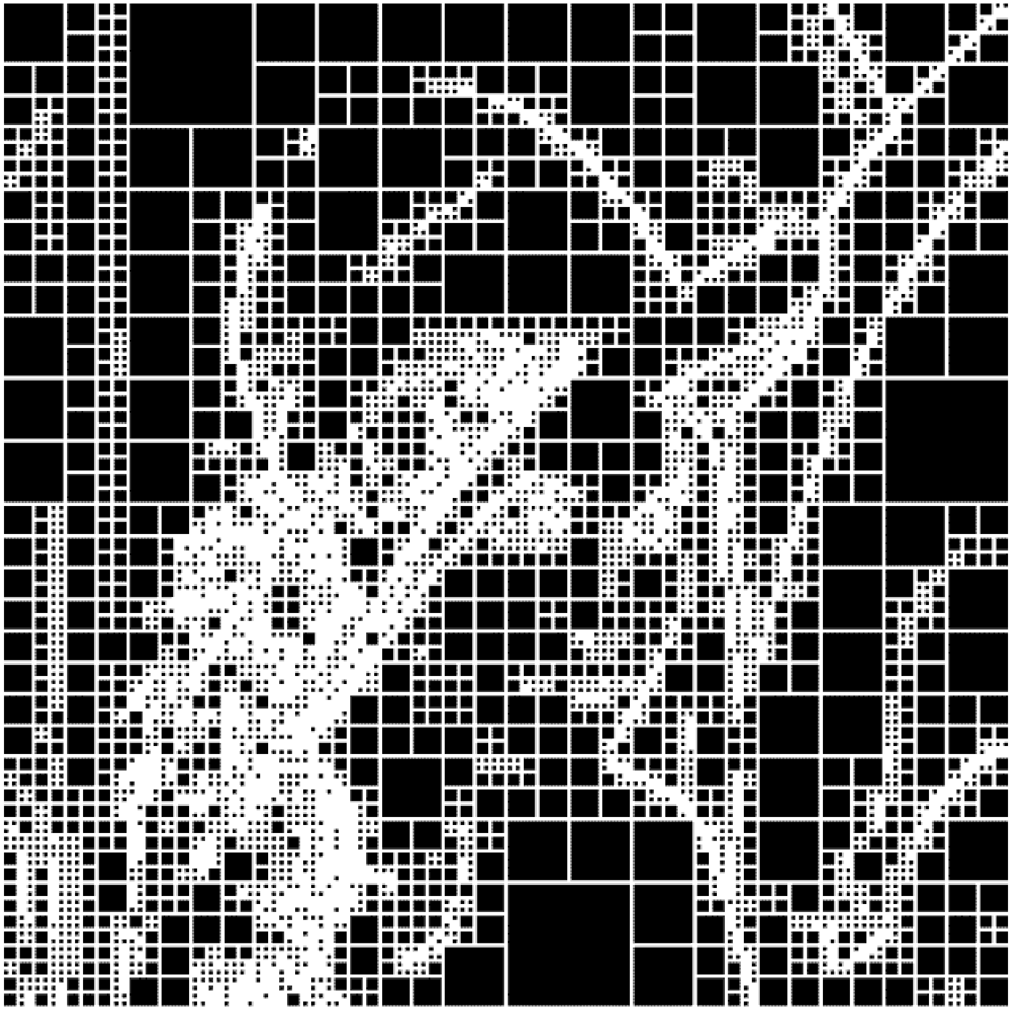
Representations and Features

- Feature representation usually uses a simple 1-D string of values to specify a certain feature such as the shape or the texture.
- Simple feature representation techniques:
  - Run-length representation – boundary and shape,
  - Quad-Tree representation – boundary and shape,
  - Chain-code representation –boundary and shape,
- Translation and rotation invariant techniques:
  - Fourier descriptors – boundary and shape,
  - Moment representation – texture,
  - Histogram feature representation– texture.

Quad-Tree Representation Example



Feature Detection and Classification

- Feature detection is to identify the presence of a certain type of feature or object in an image.
- Feature detection is usually achieved by studying the statistic variations of certain regions and their backgrounds to locate unusual activities.
- Once an interesting feature has been detected, the representation of this feature will be used to compare with all possible features known to the processor. A statistical classifier will produce a feature type that has the closest similarity (or maximum likelihood) to the testing feature.
- Data collection and analysis (or the training process)have to be performed at the classifier before any classification.

ATR Example

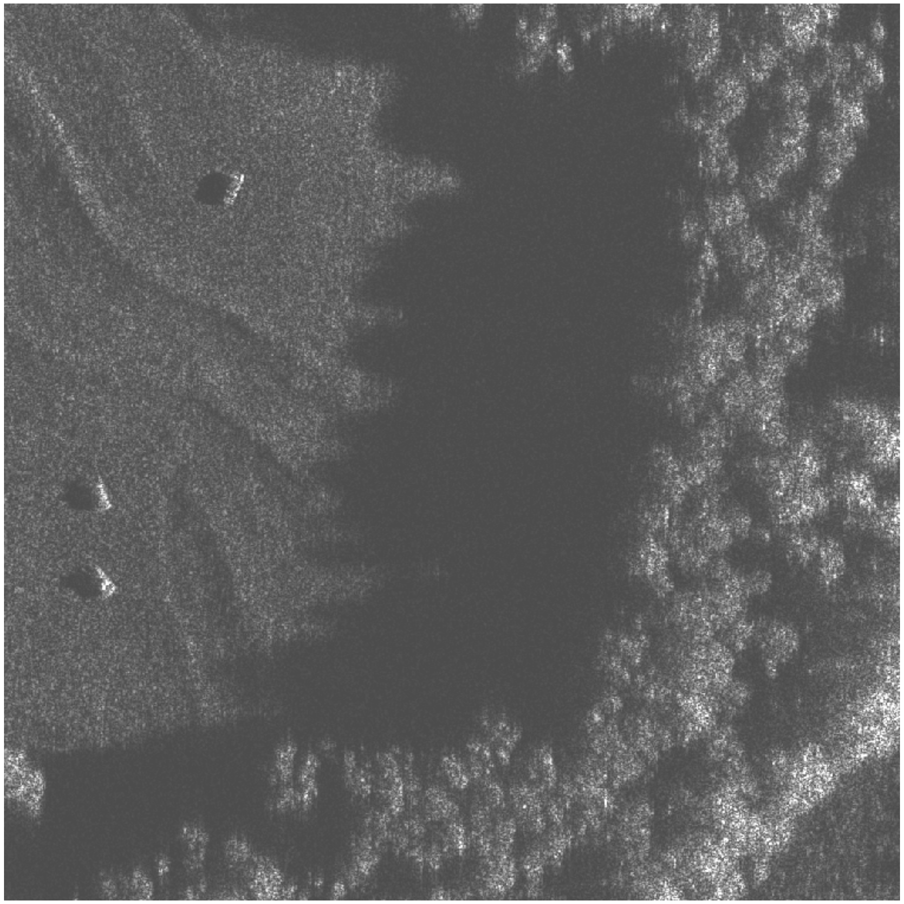
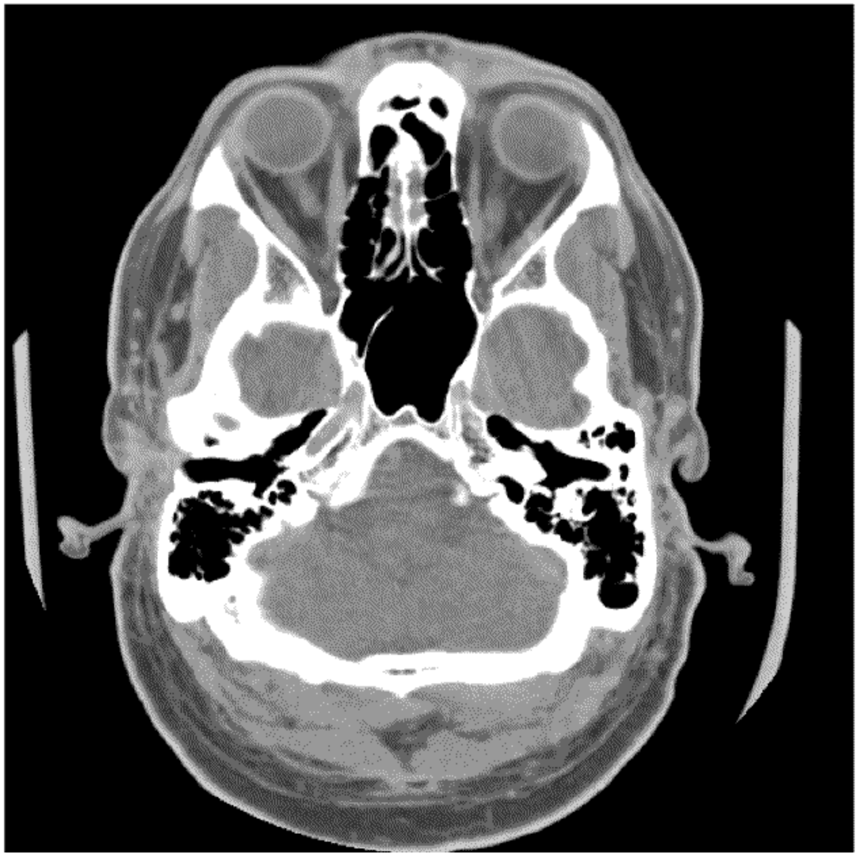


Image size 1024x1024 in floating point.

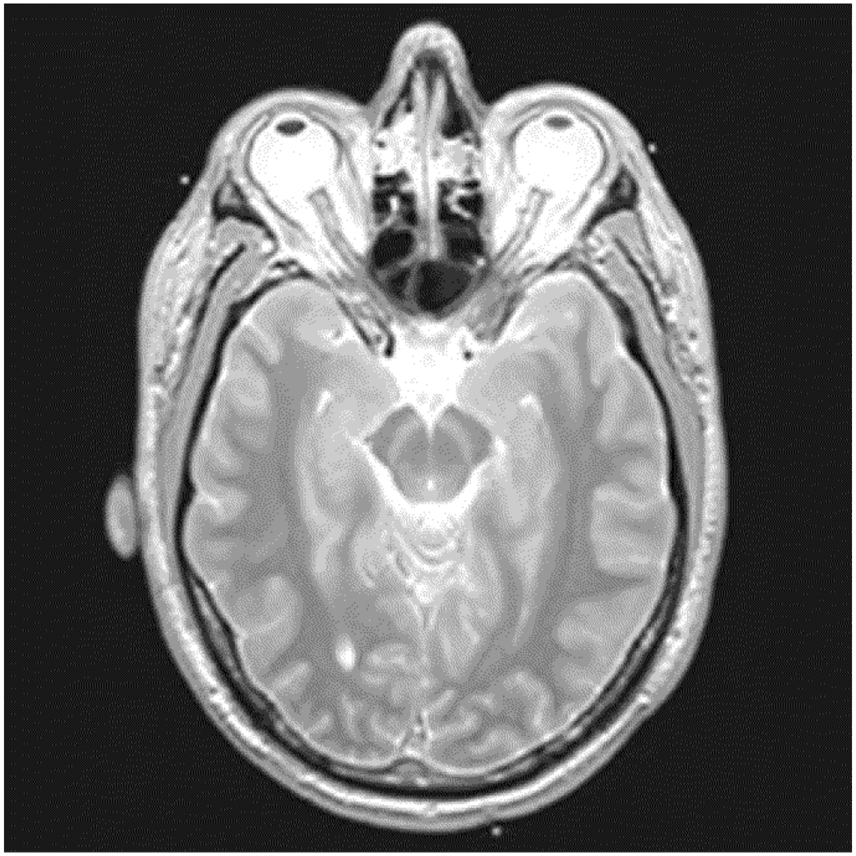
6. Computed Tomography

- Besides the natural images acquired from conventional optical cameras, computer synthesized images become more and more important in many application fields.
- Non-invasive imaging modalities allow people to view objects that can not be seen by human eye or camera,
  - Internal organ of human body,
  - Damaged part inside an airplane wing,
  - Cloud covered city,
  - Dark night battle field,
  - Underground oil field…

Medical Imaging Examples



Computed Tomography

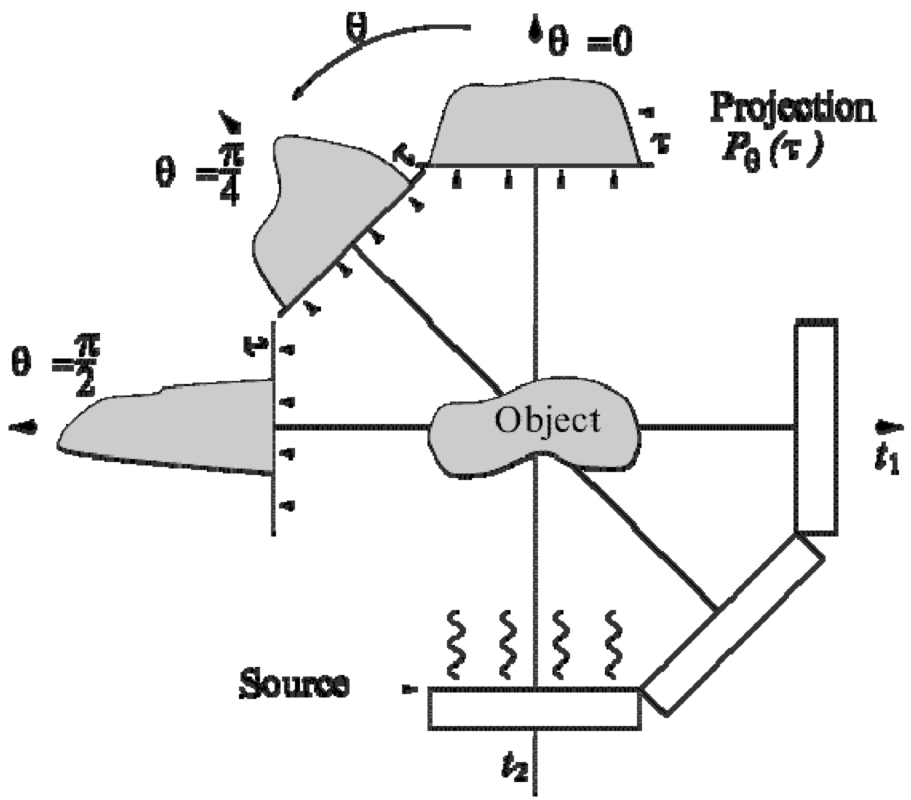


Magnetic Resonance Imaging

Sensor Imaging Examples

Synthetic Aperture Radar Imaging

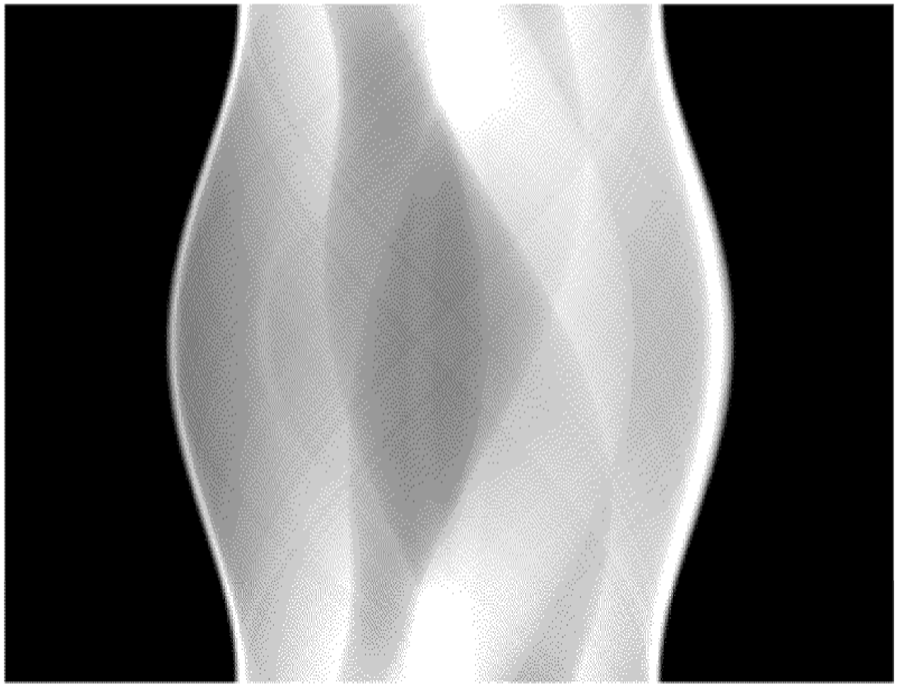
Reconstruction from Projection



$$P_\theta(\tilde{\Omega}) = X(\Omega_1, \Omega_2)\Big|_{\substack{\Omega_1 = \tilde{\Omega}\cos\theta \\ \Omega_2 = \tilde{\Omega}\sin\theta}}$$

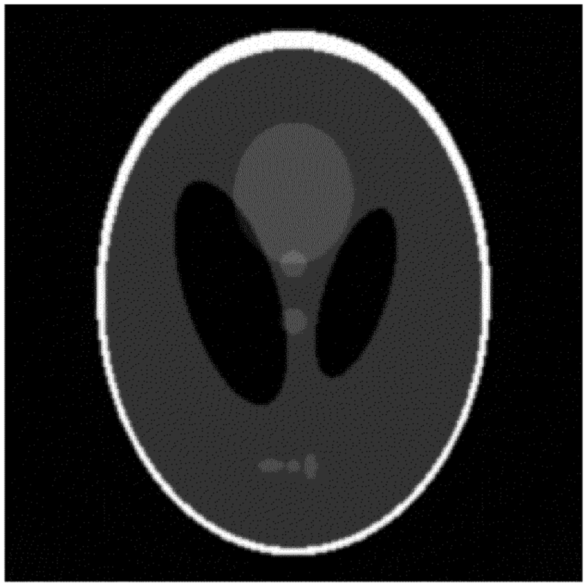
Projection Example

Phantom (256x256)



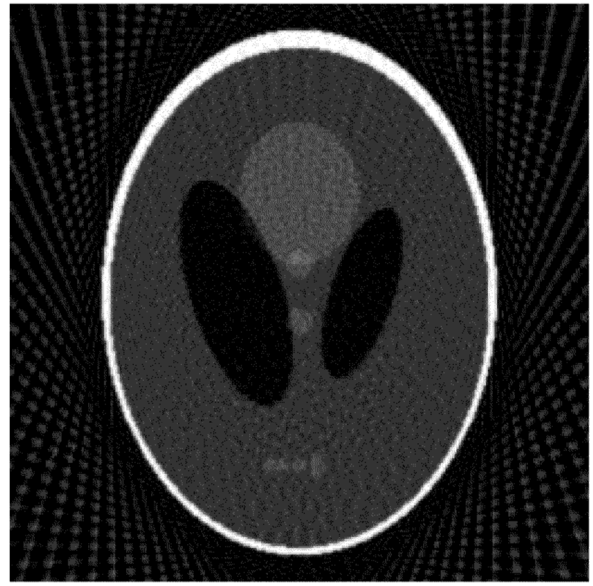
180 projections

Reconstruction Examples



180 projections

90 projections



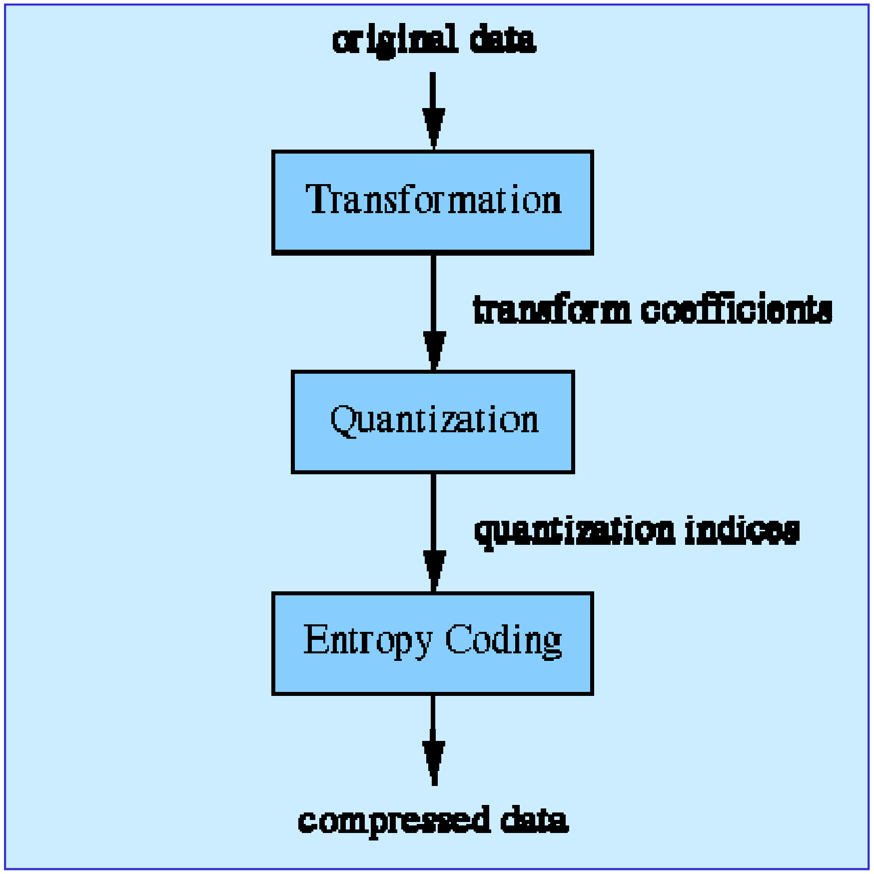
45 projections

7. Image and Video Compression

- Image and video compression:

  to reduced the number of bits requires to represent visual data at an acceptable fidelity.
- Why:
  - increase speed of visual data transmission,
  - reduce memory requirement.
- How:
  - exploit the redundancy within the visual data.
    - spatial redundancy,
    - temporal redundancy.

Elements of Image/Video Compression



Three stage image/video coding structure.

Data Transformation

- Data transformation:

  represent an input data array by a new data array through an invertible data transform method.
- Why:
  - energy compaction,
  - de-correlation,
  - helpful data structure.
- How:
  - discrete cosine transform (DCT),
  - subband/wavelet transform.

Example of (8x8) 2-D DCT

$$X[k_1,k_2]=\frac{1}{4}\sum_{n_1=0}^{7}\sum_{n_2=0}^{7}C_{k_1}C_{k_2}x[n_1,n_2]\cos\left[\frac{(2n_1+1)k_1\pi}{16}\right]\cos\left[\frac{(2n_2+1)k_2\pi}{16}\right]$$

$$x[n_1,n_2]=\frac{1}{4}\sum_{k_1=0}^{7}\sum_{k_2=0}^{7}C_{k_1}C_{k_2}X[k_1,k_2]\cos\left[\frac{(2n_1+1)k_1\pi}{16}\right]\cos\left[\frac{(2n_2+1)k_2\pi}{16}\right]$$

$$C_{k_1},C_{k_2}=\begin{cases}\frac{1}{\sqrt{2}} & \text{for } k_1,k_2=0\\ 1 & \text{otherwise}\end{cases}$$

79	75	79	82	82	86	94	94
76	78	76	82	83	86	85	94
72	75	67	78	80	78	74	82
74	76	75	75	86	80	81	79
73	70	75	67	78	78	79	85
69	63	68	69	75	78	82	80
76	76	71	71	67	79	80	83
72	77	78	69	75	75	78	78

2-D DCT (8x8) →

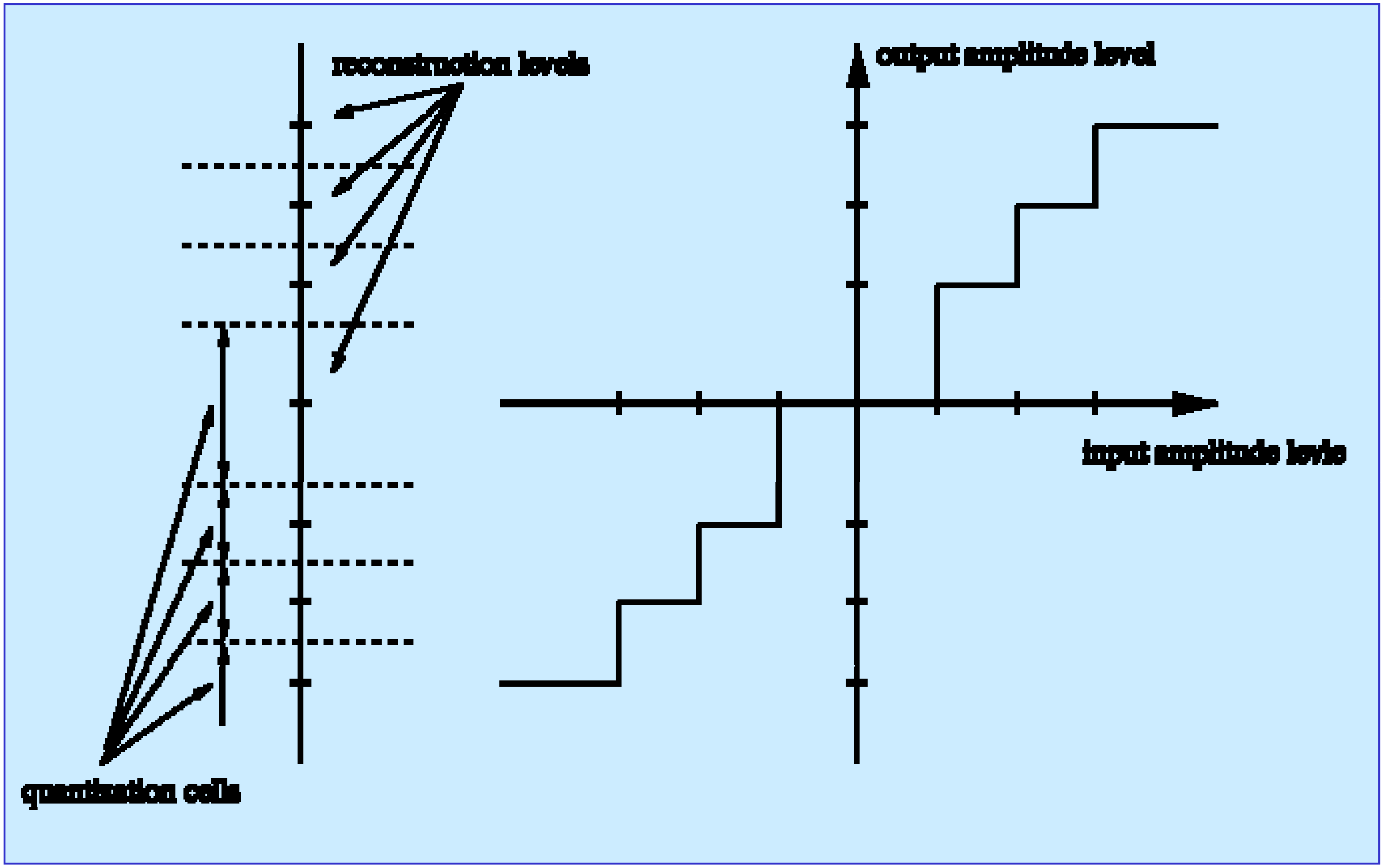
619	−29	8	2	1	−3	0	1
22	−6	−4	0	7	0	−2	−3
11	0	5	−4	−3	4	0	−3
2	−10	5	0	0	7	3	2
6	2	−1	−1	−3	0	0	8
1	2	1	2	0	2	−2	−2
−8	−2	−4	1	2	1	−1	1
−3	1	5	−2	1	−1	1	−3

Quantization

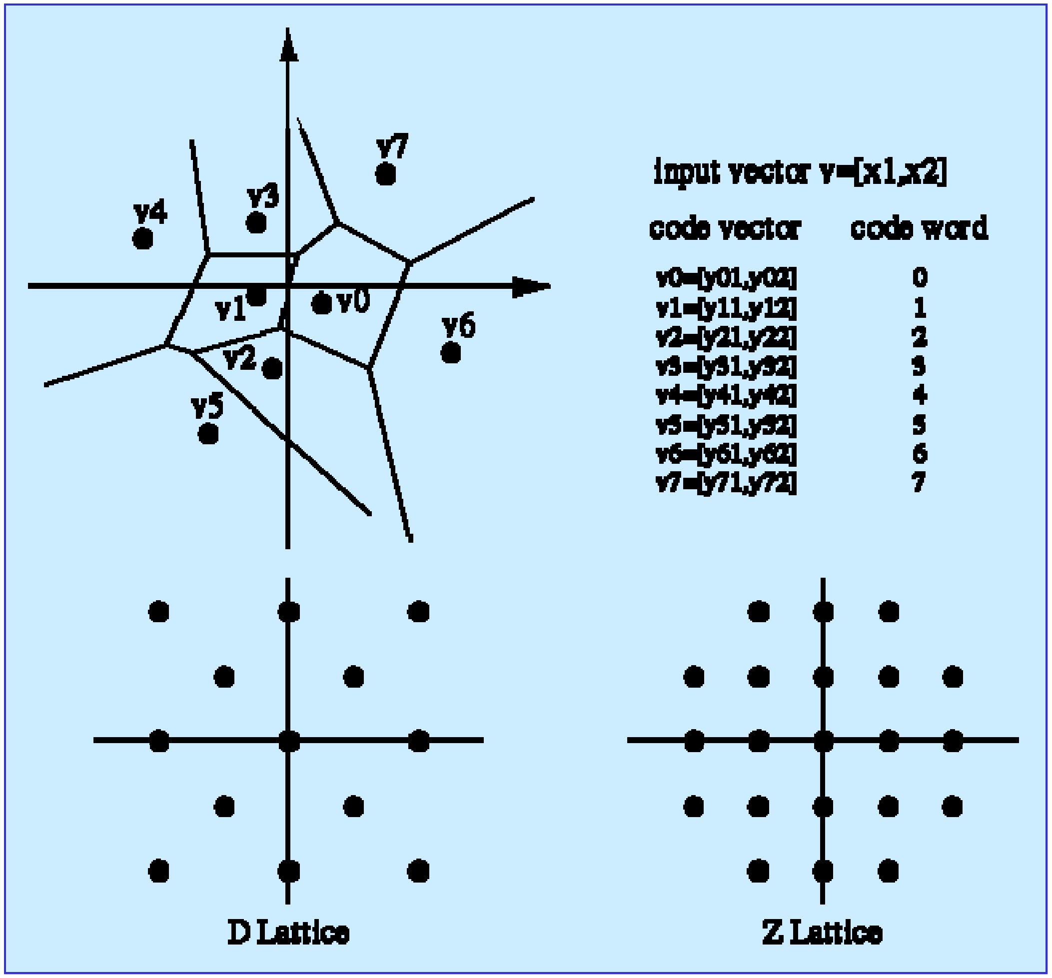
- Quantization:

  map a large number of input amplitude levels to a small number of output amplitude levels with non-recoverable loss of quality.
- Why:
  - reduced level of amplitude $\Rightarrow$ reduced number of bits required to represent each pixel.
- How:
  - scalar quantization (SQ),
  - vector quantization (VQ).

Example of SQ



Examples of VQ



Entropy Coding

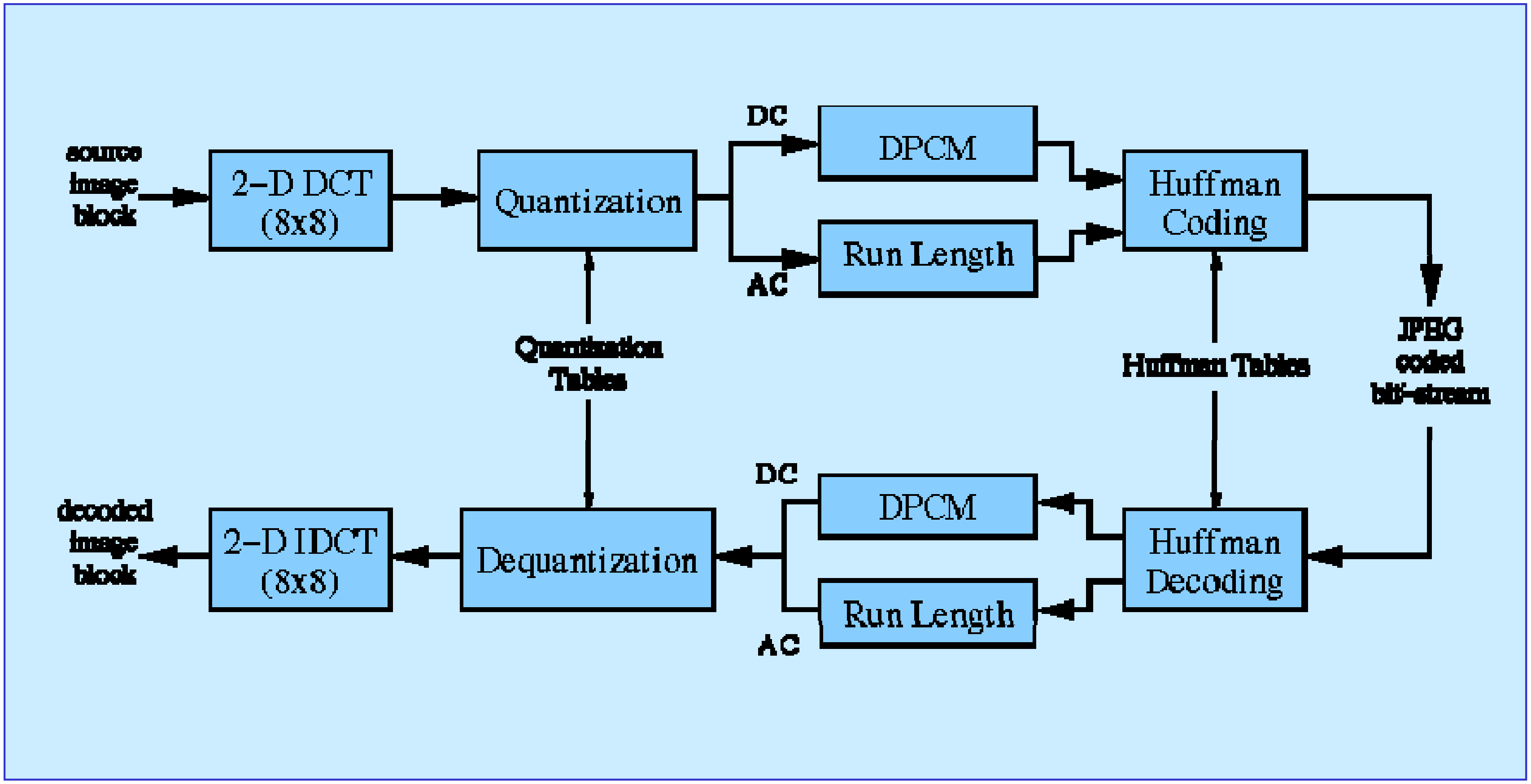
- Entropy coding:

  use codewords with different lengths to losslessly represent symbols with different probabilities.
- Why:
  - use small number of bits to represent more frequent symbols and use large number of bits to represent less frequent symbols so that the length of overall symbols can be reduced.
- How:
  - Huffman coding,
  - Arithmetic coding.

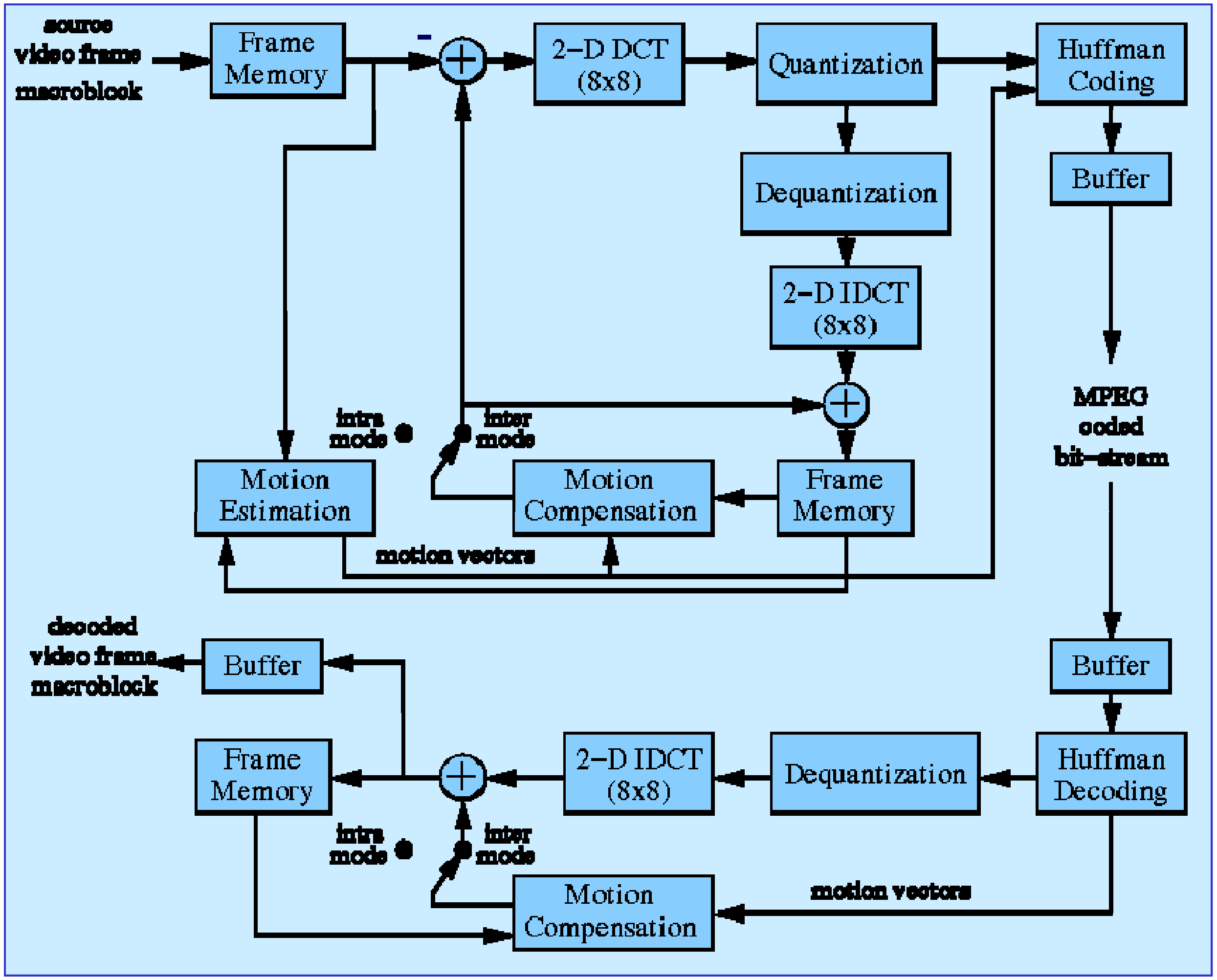
Example of Huffman Coding

Symbol	Probability Table	Code Word
A	0.12	100
E	0.42	0
I	0.09	1011
O	0.30	11
U	0.07	1010

Joint Photographic Experts Group (JPEG)



Moving Pictures Experts Group (MPEG)

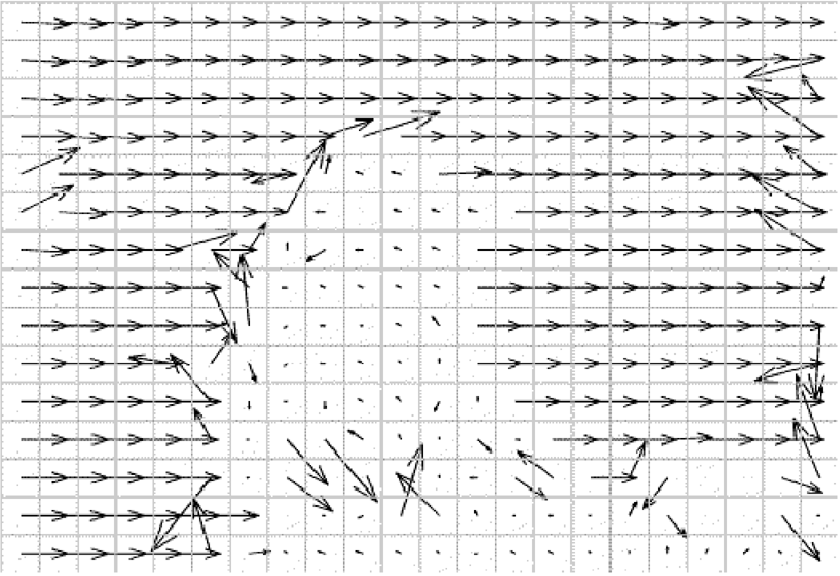


Example of Motion Compensation (1)

Previous frame

Current frame

Example of Motion Compensation (2)



Motion vector field

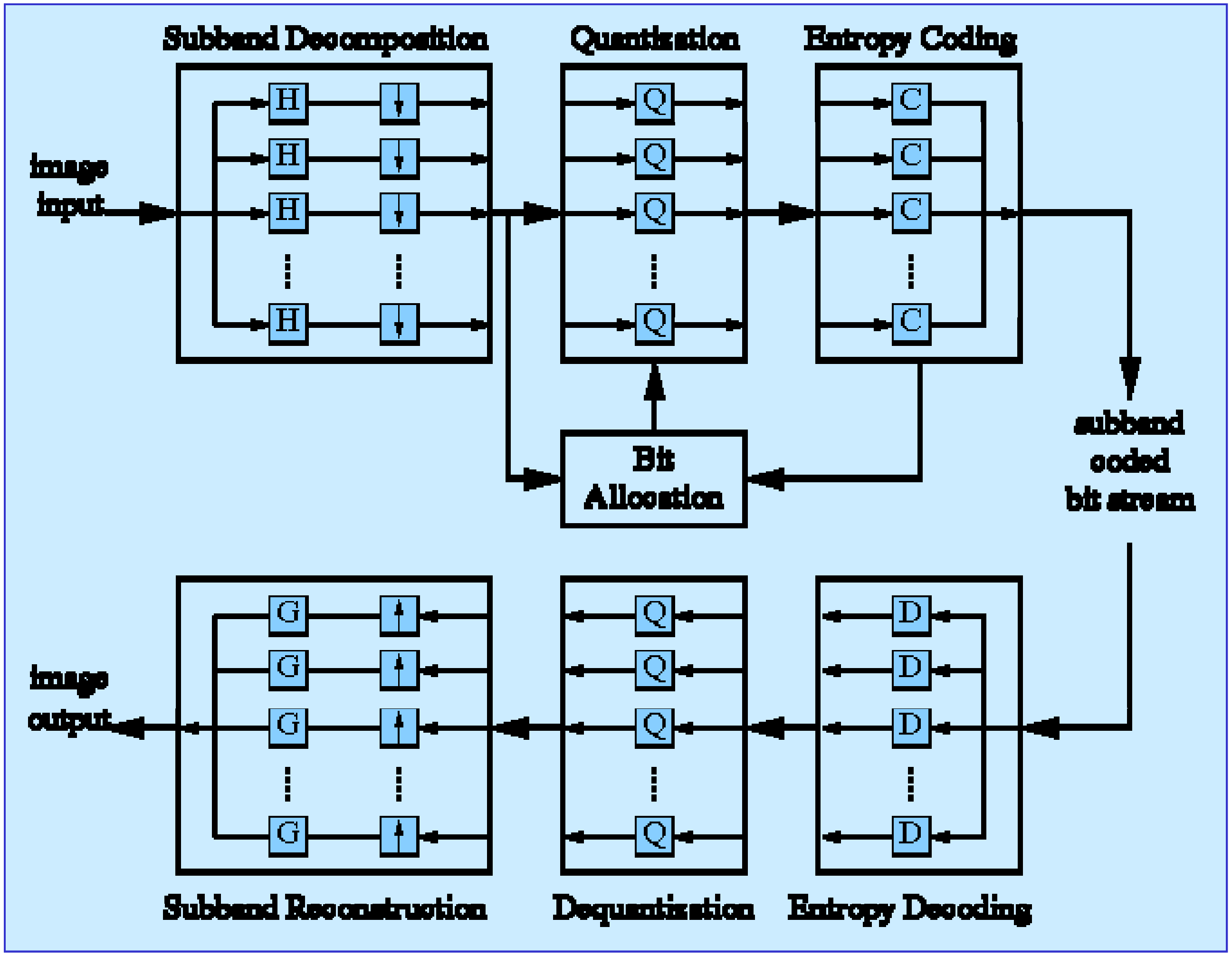
Prediction of current frame

Example of Motion Compensation (3)

Residual frame with MC

Residual frame with direct difference

Subband Image Coding



Examples of Compressed Images (1)

JPEG Coder

JPEG 2000 Coder

Bit Rate 0.25 bpp $\Rightarrow$ compression ratio 32:1.

Examples of Compressed Images (2)

SPIHT Coder

QuadTree Coder

Bit Rate 0.25 bpp ⇒ compression ratio 32:1.

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